Gauge Non-Singlet (GNS) Inflation in SUSY GUTs

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Motivation

Inflation is very sucessful in explaining

- ... why the Universe is homogeneous and isotropic on large scales
- ... why the Universe is almost perfectly spatially flat
- ... the possible origin of the small-scale fluctuations
- ... the absence of topological defects

Hybrid inflation typically involves energy scales around the GUT scale $\Lambda \sim 10^{15} - 10^{16}$GeV

$\longleftrightarrow$

Particle physics only explored experimentally up to the TeV scale $E \lesssim$ TeV

The connection between Inflation and Particle Physics remains unclear !

Motivation

To make this connection, our strategy will be the following:

> Assuming a supersymmetric GUT at the energy scale relevant for (hybrid) inflation we want to identify the inflaton with the scalar superpartner of some "matter field".

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To make this connection, our strategy will be the following:

Assuming a supersymmetric GUT at the energy scale relevant for (hybrid) inflation we want to identify the inflaton with the scalar superpartner of some “matter field”.

However, this is not without problems

In general, the inflaton is now a gauge non-singlet !

The inflaton potential might receive large D-term contributions. $\Rightarrow$ violates slow-roll

Two-loop mass corrections might drive the inflaton mass above the Hubble scale. $\Rightarrow m^2 > H\ ,\ |\eta| > 1$

The production of stable topological defects has to be avoided.

$U(1)$ Toy Model

To illustrate our approach, let's first consider the simplest case, an inflaton Φ charged under $G = U(1)$.

- The inflaton is now charged $\longrightarrow$ What about the D-term contributions to its potential ?

$$V_D = \sum_a \frac{g^2}{2} \left(\Phi^\dagger \mathcal{T}^a \Phi\right)^2 = \frac{g^2}{2} \left(\Phi^\dagger \cdot q \cdot \Phi\right)^2 = \frac{g^2 q^2}{2} |\Phi|^4 \neq 0 \quad \text{for} \quad \langle \Phi \rangle \neq 0$$

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- Consider two inflaton fields $\Phi, \bar{\Phi}$ in conjugate reps. (i.e. in this case with opposite charges) !

$$V_D = \sum_a \frac{g^2}{2} \left(\Phi^\dagger\, \mathcal{T}^a\, \Phi + \bar{\Phi}^\dagger\, \bar{\mathcal{T}}^a\, \bar{\Phi}\right)^2 = \frac{g^2 q^2}{2} \left(|\Phi|^2 - \left|\bar{\Phi}\right|^2\right)^2 = 0$$

$$\text{for } |\langle\Phi\rangle| = \left|\langle\bar{\Phi}\rangle\right| \neq 0$$

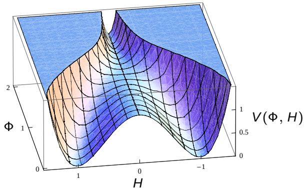
- General strategy: Look for D-flat directions in field space and impose the resulting constraints on the F-term potential which is responsible for inflation !

$U(1)$ Toy Model

Let's now consider the following Superpotential, which is of the "tribrid" form ***[Antusch et al. '09]***

$$W = \kappa S\,(H\,\bar{H} - M^2) + \frac{\zeta}{\Lambda}(H\,\bar{H})(\Phi\,\bar{\Phi}) + \ldots$$

- S is kept at 0 during and after inflation by ***SUGRA corrections*** and provides the vacuum energy by its F-term.
- The waterfall fields $\bar{H}$ and H remain at 0 during inflation and end inflation by acquiring a vev.
- $\bar{\Phi}$ and Φ act as inflatons.



Tree-level potential in the D-flat valley

For $\left|\langle\bar{\Phi}\rangle\right| = |\langle\Phi\rangle|$ and $\langle\bar{H}\rangle = \langle H\rangle = \langle S\rangle = 0$ inflation proceeds along a D-flat valley. On this trajectory the inflaton potential is tree-level flat!

SUGRA Issues

In the tribrid setup, the η **-problem of SUGRA** can be solved by Heisenberg symmetry.

Take the tribrid-like superpotential and the following Kähler potential:

$$K = f(\rho) + H^\dagger H + \bar{H}^\dagger \bar{H} + (1 + \kappa_S |S|^2 + \kappa_\rho \rho)|S|^2 + ...$$

- Heisenberg symmetry invariant combination
  $\rho = T + T^* - \Phi^\dagger \Phi - \bar{\Phi}^\dagger \bar{\Phi}$
- Transformation to the (diagonal) $(\rho, \Phi, \bar{\Phi})$-basis
  $\Rightarrow$ Tree-level potential flat in the inflaton direction
- κ_S - coupling can provide the necessary large mass for S to be stabilized at 0
- κ_ρ - coupling helps to stabilize the modulus field during inflation

For further detail, see ***[Antusch et al. '09]***

$U(1)$ Toy Model

- The mass spectrum on the inflationary trajectory $\langle S\rangle = \langle H\rangle = \langle \bar{H}\rangle = 0$ and $|\langle\Phi\rangle| = \left|\langle\bar{\Phi}\rangle\right| \equiv |\phi|$ reads

  1 Dirac fermion with squared mass $m_F^2 = \frac{|\zeta|^2|\phi|^4}{\Lambda^2}$
  2 complex scalars with mass $m_S^2 = \frac{|\zeta|^2|\phi|^4}{\Lambda^2} \pm |\kappa|^2 M^2$

- The critical values is reached for

$$\left|\phi^{\text{crit}}\right| = \sqrt{\frac{|\kappa|M}{|\zeta|}}$$

- Insertion of the inflaton dependent mass values in the formula for the Coleman-Weinberg one-loop effective potential

$$V_{\text{loop}} = \frac{1}{64\pi^2}\text{STr}\left[\mathcal{M}^4\left(\ln\frac{\mathcal{M}^2}{Q^2} - \frac{3}{2}\right)\right]$$

  yields the necessary slope to drive inflation and leads to the following predictions

$$n_s \simeq 0.98 \qquad r \lesssim 0.01 \qquad M \simeq 10^{15} - 10^{16}\text{GeV}$$

Inflation in Pati-Salam

A more realistic example: Sneutrino inflation in Pati-Salam
$G_{PS} = SU(4)_C \times SU(2)_L \times SU(2)_R$ ***[Pati, Salam '74]***

Minimalist field content:

$$R_i^c = (\bar{\mathbf{4}}, \mathbf{1}, \bar{\mathbf{2}}) = \begin{pmatrix} u_i^c & u_i^c & u_i^c & \nu_i^c \\ d_i^c & d_i^c & d_i^c & e_i^c \end{pmatrix} \qquad \bar{R}^c = (\mathbf{4}, \mathbf{1}, \mathbf{2}) = \begin{pmatrix} \bar{u}^c & \bar{u}^c & \bar{u}^c & \bar{\nu}^c \\ \bar{d}^c & \bar{d}^c & \bar{d}^c & \bar{e}^c \end{pmatrix}$$

$$H^c = (\bar{\mathbf{4}}, \mathbf{1}, \bar{\mathbf{2}}) = \begin{pmatrix} u_H^c & u_H^c & u_H^c & \nu_H^c \\ d_H^c & d_H^c & d_H^c & e_H^c \end{pmatrix} \qquad \bar{H}^c = (\mathbf{4}, \mathbf{1}, \mathbf{2}) = \begin{pmatrix} \bar{u}_H^c & \bar{u}_H^c & \bar{u}_H^c & \bar{\nu}_H^c \\ \bar{d}_H^c & \bar{d}_H^c & \bar{d}_H^c & \bar{e}_H^c \end{pmatrix}$$

$$S, X = (\mathbf{1}, \mathbf{1}, \mathbf{1})$$

$i = 4$ (four generations) $\rightarrow$ 3 light generations after inflation !

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Superpotential:

$$W = \kappa S \left(\frac{\langle X \rangle}{\Lambda} H^c \bar{H}^c - M^2 \right)$$
$$+ \frac{\lambda_{ij}}{\Lambda} (R_i^c \bar{H}^c)(R_j^c \bar{H}^c) + \frac{\gamma}{\Lambda} (\bar{R}^c H^c)(\bar{R}^c H^c) + \frac{\zeta_i}{\Lambda} (R_i^c \bar{R}^c)(H^c \bar{H}^c) + \frac{\xi_i}{\Lambda} (R_i^c \bar{H}^c)(\bar{R}^c H^c)$$
$$+ \ldots$$

Sneutrino Trajectory

Special trajectory : Sneutrino inflation !

$$\langle R_1^c \rangle = \begin{pmatrix} 0 & 0 & 0 & \langle \nu^c \rangle \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad \langle \bar{R}^c \rangle = \begin{pmatrix} 0 & 0 & 0 & \langle \bar{\nu}^c \rangle \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad \langle R_{i\neq 1}^c \rangle = 0$$

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- D-flatness $\Rightarrow |\langle \nu^c \rangle| = |\langle \bar{\nu}^c \rangle|$
- $\langle H^c \rangle = \langle \bar{H}^c \rangle = 0$ during inflation due to large masses from the F-term potential. $\langle S \rangle = 0$ due to SUGRA corrections.
- At some critical value ν_{crit} one or more component fields of $H^c, \bar{H}^c$ become tachyonic and end inflation by acquiring a vev ("waterfall").

$$\nu_{\text{crit}} = \sqrt{\frac{2|\kappa|M}{|\zeta|}} \quad \text{for} \quad u_H^c, d_H^c, e_H^c, \ldots$$

$$\nu_{\text{crit}} = \sqrt{\frac{2|\kappa|M}{|\zeta+\xi\pm 2\gamma|}} \quad \text{for} \quad \Re(\bar{\nu}_H^c - \nu_H^c), \Im(\bar{\nu}_H^c - \nu_H^c)$$

↔ Preferred direction $\Rightarrow$ No monopoles !

Non-Singlet Inflaton ?

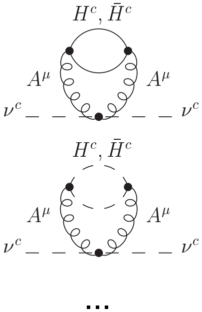
What about the problems mentioned in the introduction?

- D-term contributions $\rightarrow$ D flat valley ✓
- Monopoles $\rightarrow$ Preferred direction ✓
- Domain walls $\rightarrow$ Higher dim. operators, tilt of potential ✓

Non-Singlet Inflaton ?

What about the problems mentioned in the introduction?

- D-term contributions $\rightarrow$ D flat valley ✓
- Monopoles $\rightarrow$ Preferred direction ✓
- Domain walls $\rightarrow$ Higher dim. operators, tilt of potential ✓
- Two loop contributions to the inflaton mass



- Typical problem: 2-loop mass contribution for non-singlets

$$\delta m^2 \sim \frac{g^4}{(4\pi)^2} \frac{|W_S|^2}{m_F^2} > H^2 \quad \textbf{\textit{[Dvali '95]}}$$

- However in our class of models: Gauge symmetry broken in the inflaton direction

$$\delta m^2 \sim \frac{g^4}{(4\pi)^2} \frac{\mu^4}{M_g^2} \ll H^2 \qquad ✓$$

Road to $SO(10)$

- Make the model left-right symmetric
  - Add $L_i = (\mathbf{4}, \mathbf{2}, \mathbf{1}), \bar{L} = (\bar{\mathbf{4}}, \bar{\mathbf{2}}, \mathbf{1}), H = (\mathbf{4}, \mathbf{2}, \mathbf{1})$ and $\bar{H} = (\bar{\mathbf{4}}, \bar{\mathbf{2}}, \mathbf{1})$ to the field content
  - Two sectors of inflation, "inflaton race"
- Unify left- and right-charged leptoquark superfields

$$
\begin{aligned}
\mathbf{16} = (\mathbf{4}, \mathbf{2}, \mathbf{1}) \oplus (\bar{\mathbf{4}}, \mathbf{1}, \bar{\mathbf{2}}) \quad &\rightarrow \quad \boldsymbol{F_i} = L_i \oplus R_i^c \ , \ \boldsymbol{H} = H \oplus H^c \\
\overline{\mathbf{16}} = (\bar{\mathbf{4}}, \bar{\mathbf{2}}, \mathbf{1}) \oplus (\mathbf{4}, \mathbf{1}, \mathbf{2}) \quad &\rightarrow \quad \bar{\boldsymbol{F}} = \bar{L} \oplus \bar{R}^c \ , \ \bar{\boldsymbol{H}} = \bar{H} \oplus \bar{H}^c
\end{aligned}
$$

- $SO(10)$ superpotential

$$
\boxed{
\begin{aligned}
W = \kappa S \left(\frac{\langle X \rangle}{\Lambda} H\bar{H} - M^2 \right) \\
+ \frac{\lambda_{ij}}{\Lambda}(F_i F_j \bar{H}\bar{H}) + \frac{\gamma}{\Lambda}(\bar{F}\bar{F}HH) + \frac{\zeta_i}{\Lambda}(F_i \bar{F} H \bar{H}) + ...
\end{aligned}
}
$$

Summary

- Connection between inflation and particle physics still very much under investigation
- Embedding of inflation into SUSY GUTs $\rightarrow$ inflaton a gauge non-singlet
- New class of models: Gauge Non-Singlet (GNS) Inflation in SUSY GUTs
- Inflaton gauge interactions and D-term contributions to the inflaton potential entail certain problems for the realization of slow-roll inflation ...
- ... we provided a proof of existence: Sneutrino trajectory is a viable trajectory for inflation in PS or $SO(10)$ that solves these problems.
- More generic D-flat trajectories do also exist, which might lead to more complicated (multi-field) inflationary dynamics.